eRD14 – EIC PID consortium

- An integrated program for particle identification (PID) for a future Electron-Ion Collider (EIC) detector.

M. Alfred, L. Allison, M. Awadi, B. Azmoun, F. Barbosa, W. Brooks, T. Cao, M. Chiu, E. Cisbani, M.Contalbrigo, A. Datta, A. Del Dotto, M. Demarteau, J.M. Durham, R. Dzhygadlo, D. Fields, Y. Furletova, C. Gleason, M. GrossePerdekamp, J. Harris, X. He, H. van Hecke, T. Horn, J. Huang, C. Hyde, Y. Ilieva, G. Kalicy, M. Kimball, E. Kistenev, Y. Kulinich, M. Liu, R. Majka, J. McKisson, R. Mendez, P. Nadel-Turonski, K. Park, K. Peters, T. Rao, R. Pisani, Yi Qiang, S. Rescia, P. Rossi, M. Sarsour, C. Schwarz, J. Schwiening, C.L. da Silva, N. Smirnov, H. Stien, J. Stevens, A. Sukhanov, S. Syed, A. Tate, J. Toh, C. Towell, R. Towell, T. Tsang, R. Wagner, J. Wang, C. Woody, C.P. Wong, W. Xi, J. Xie, Z.W. Zhao, B. Zihlmann, C. Zorn.

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Generic Detector R&D for an Electron Ion Collider

Advisory Committee Meeting, BNL, Jan. 26-27, 2017

Participating institutions

- Abilene Christian University (ACU)
- Argonne National Lab (ANL)
- Brookhaven National Lab (BNL)
- Catholic University of America (CUA)
- Duke University (Duke)
- Georgia State University (GSU)
- GSI Helmholtzzentrum für Schwerionenforschung, Germany (GSI)
- Howard University (HU)
- Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Italy (INFN-Ferrara)
- Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy (INFN-Rome)
- Istituto Superiore di Sanità, Italy (ISS)
- Jefferson Lab (JLab)
- Los Alamos National Lab (LANL)
- Old Dominion University (ODU)
- Stony Brook University (SBU)
- Universidad Técnica Federico Santa María, Chile (UTFSM)
- University of Illinois Urbana-Champaign (UIUC)
- University of New Mexico (UNM)
- University of South Carolina (USC)
- Yale University (Yale)

PID – an essential part of the EIC physics program

- The physics program for a generic EIC is outlined in the 2015 NSAC LRP, the 2012 White Paper, the 2010 INT report, etc.
- Excellent PID is crucial for achieving these physics goals!

eRD14: an integrated program for PID at an EIC

1. Develop a coherent suite of detector systems covering the full angular- and momentum range required for an EIC detector

- Different technologies in different parts of the detector
- Initial focus is on hadron ID

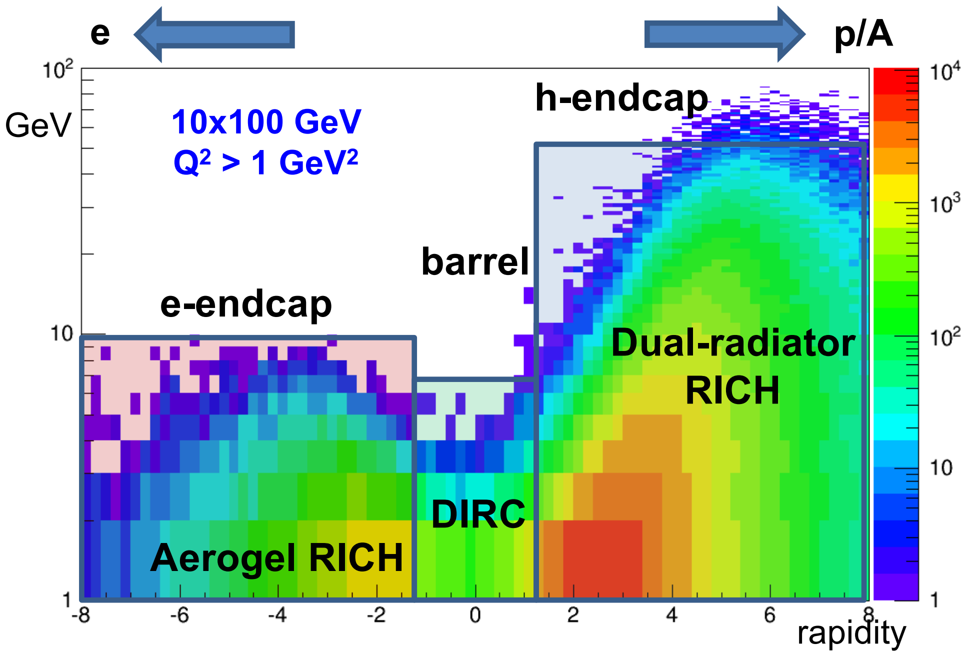
2. Find a cost-effective sensor and electronics solution

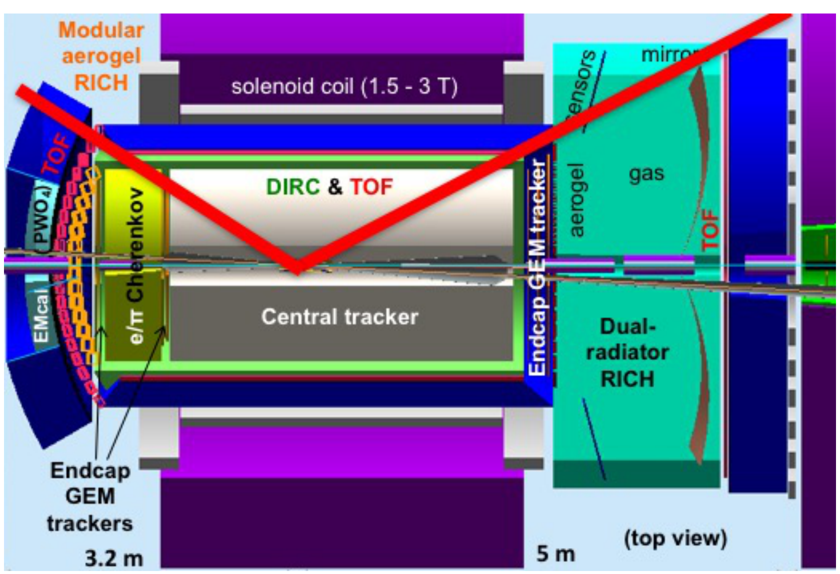
- Requirements and development of photosensors
- Road map for the electronics needed for the readout

3. Maximize synergies and minimize cost of R&D

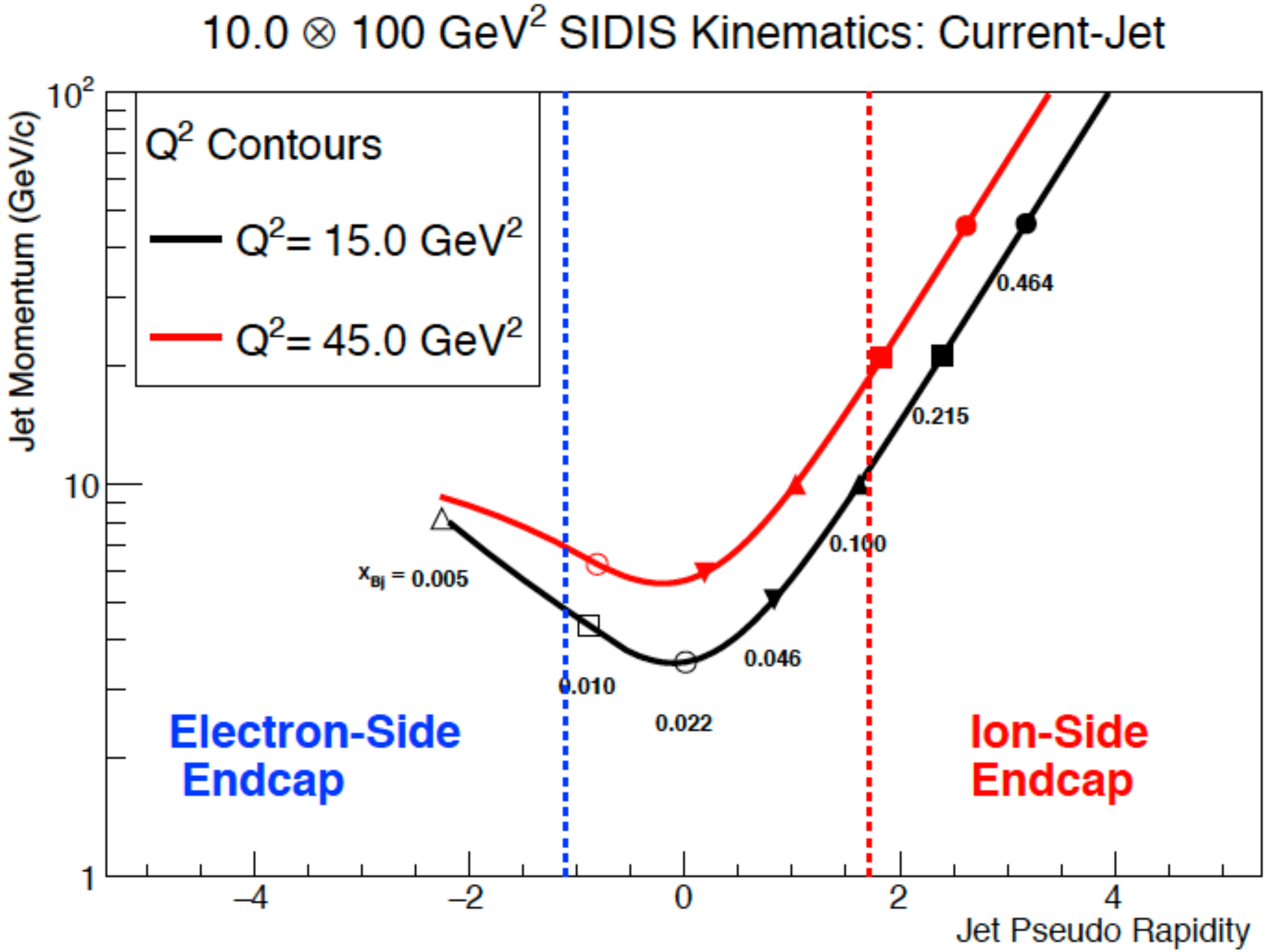
- Active collaboration within the consortium, sharing experience in weekly meetings, and drawing up common consortium goals and priorities.
- Strong synergies with non-EIC experiments and R&D programs (PANDA, CLAS12, GlueX, PHENIX, LAPPDs) resulting in large savings on hardware.

An integrated PID solution for the EIC



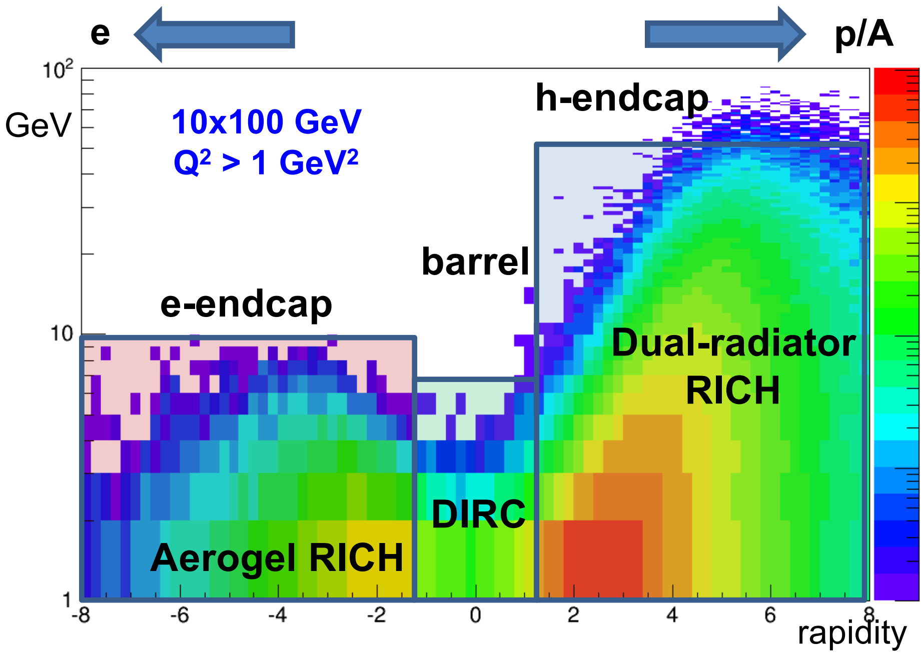


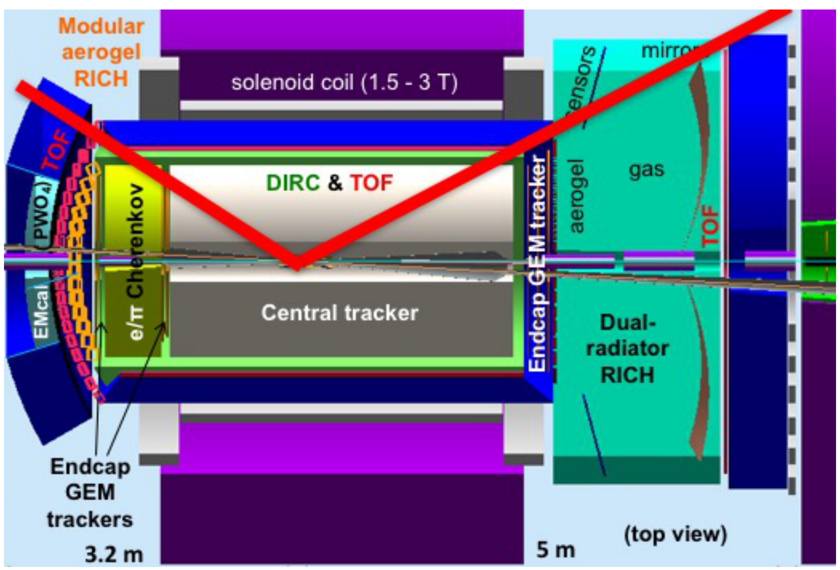
- The maximum hadron momentum in the endcaps is close to the electron and ion beam energies, respectively.
- The momentum coverage need in the central barrel is somewhat lower.
- Imaging Cherenkov detectors are the primary technology for hadron ID.
- TOF (or dE/dx) can provide a supplementary capability.
- The program pursued by the eRD14 PID consortium
  1. Fulfills all physics requirements
  2. Provides seamless integration
- Achieved through *close collaboration* within the consortium.



10.0 ⊗ 100 GeV² SIDIS Kinematics: Current-Jet
Jet Momentum (GeV/c)
Jet Pseudo Rapidity
Q² Contours
Q²= 15.0 GeV²
Q²= 45.0 GeV²
x_Bj = 0.005
0.010
0.022
0.046
0.100
0.215
0.464
Electron-Side Endcap
Ion-Side Endcap

A PID solution for the EIC - implementation





- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  pi/K/p separation up to ~50 GeV/c
- **e-endcap**: A compact aerogel RICH which can be projective
  pi/K/p separation up to ~10 GeV/c
- **barrel**: A high-performance DIRC provides a compact and cost-effective way to cover the area.
  pi/K/p separation up to ~6 GeV/c
- **TOF (and/or dE/dx in TPC)**: can cover lower momenta. Better TOF resolution would improve PID in an intermediate range.
- **Photosensors and electronics**: need to match the requirements of the new generation devices being developed – both for the final system and during the R&D phase

eRD14 detector systems: key FY17 R&D items

Dual-radiator RICH (dRICH) for h-endcap

- Integration of aerogel and gas radiators ***(Done!)***
- Adaptation to BNL endcap size and comparison with single-radiator RICH

Modular focusing aerogel RICH (mRICH) for e-endcap

- Finish test beam analysis and submit paper on photon yield ***(Done!)***
- Prepare prototype for 2nd beam test to validate PID performance

High-performance DIRC for barrel

- Validate optics using spherical lens and narrow bars through analysis of 2015 CERN test beam data and bench tests. ***(Done!)***
- Investigate potential of time-based reconstruction with wide bars through analysis of 2015 CERN test beam data and development of new cylindrical lens.

Sensors and Electronics

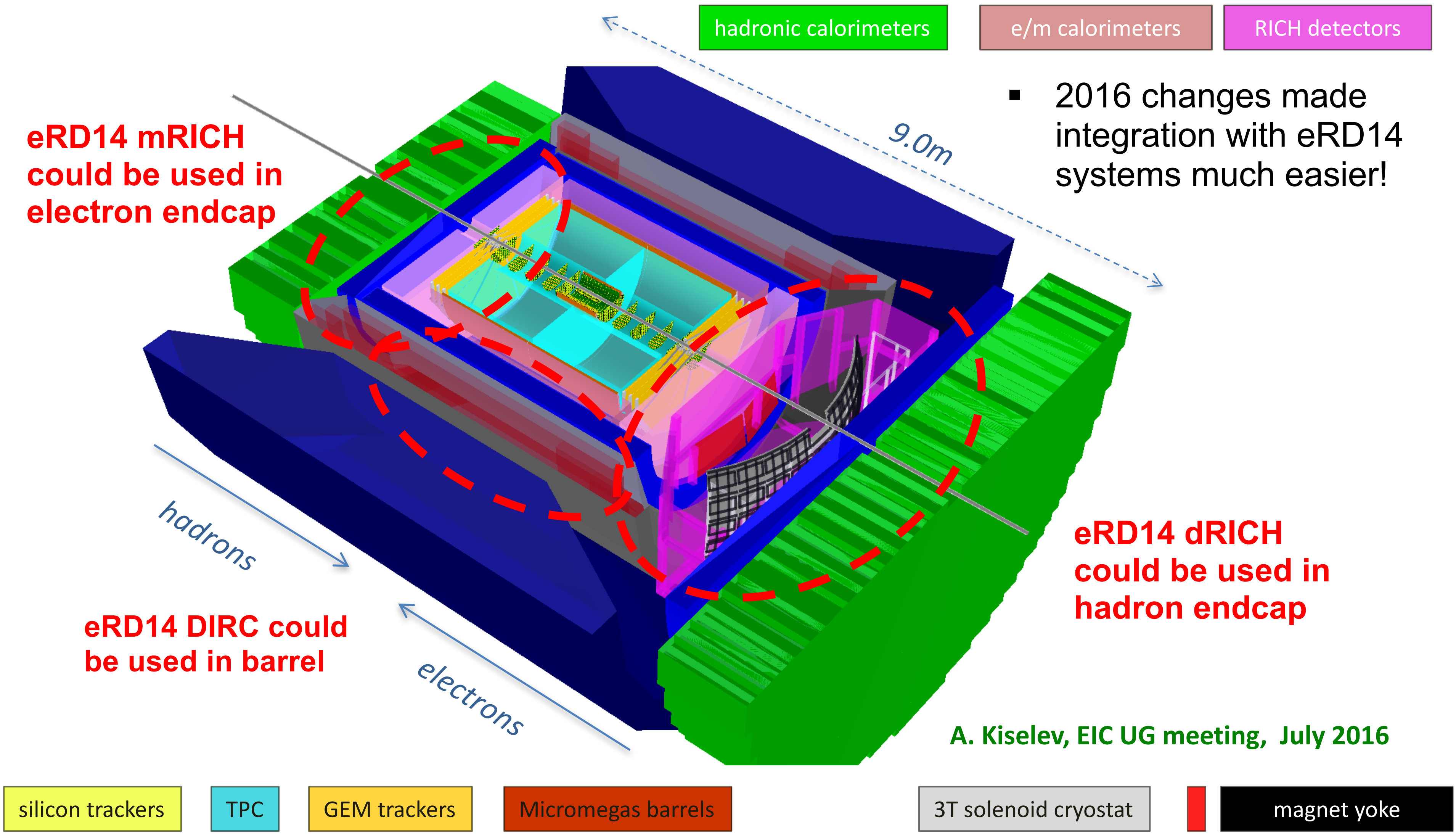
- Analyze 2016 data from MCP-PMT high-B tests and LAPPD rate tests ***(Done!)***
- Develop LAPPDs with pixelized reaout

PID in the EIC concept detectors and integration of eRD14 systems

BNL BeAST EIC central detector

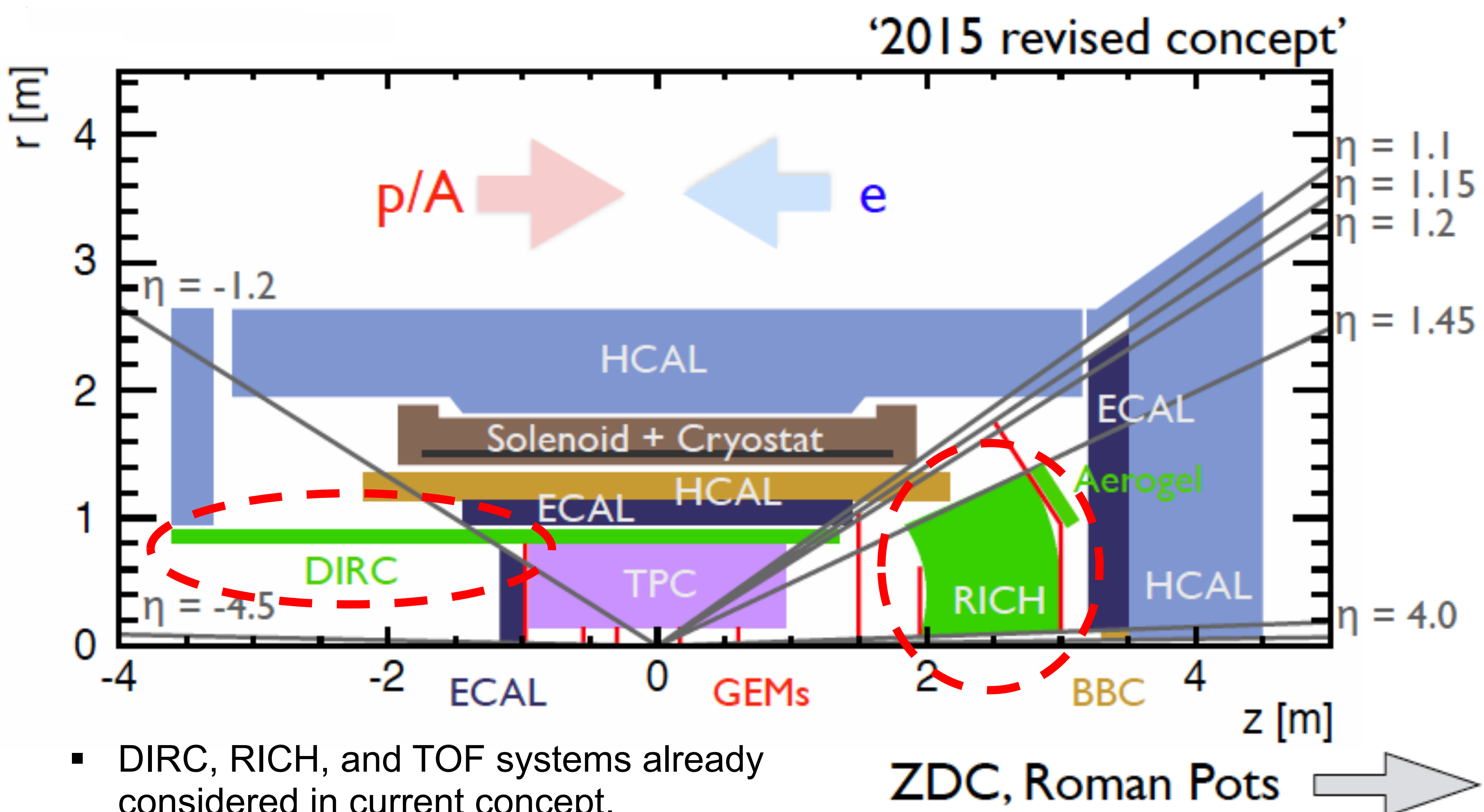
-3.5 < η < 3.5: Tracking & e/m Calorimetry (hermetic coverage)

- 2016 changes made integration with eRD14 systems much easier!



A. Kiselev, EIC UG meeting, July 2016

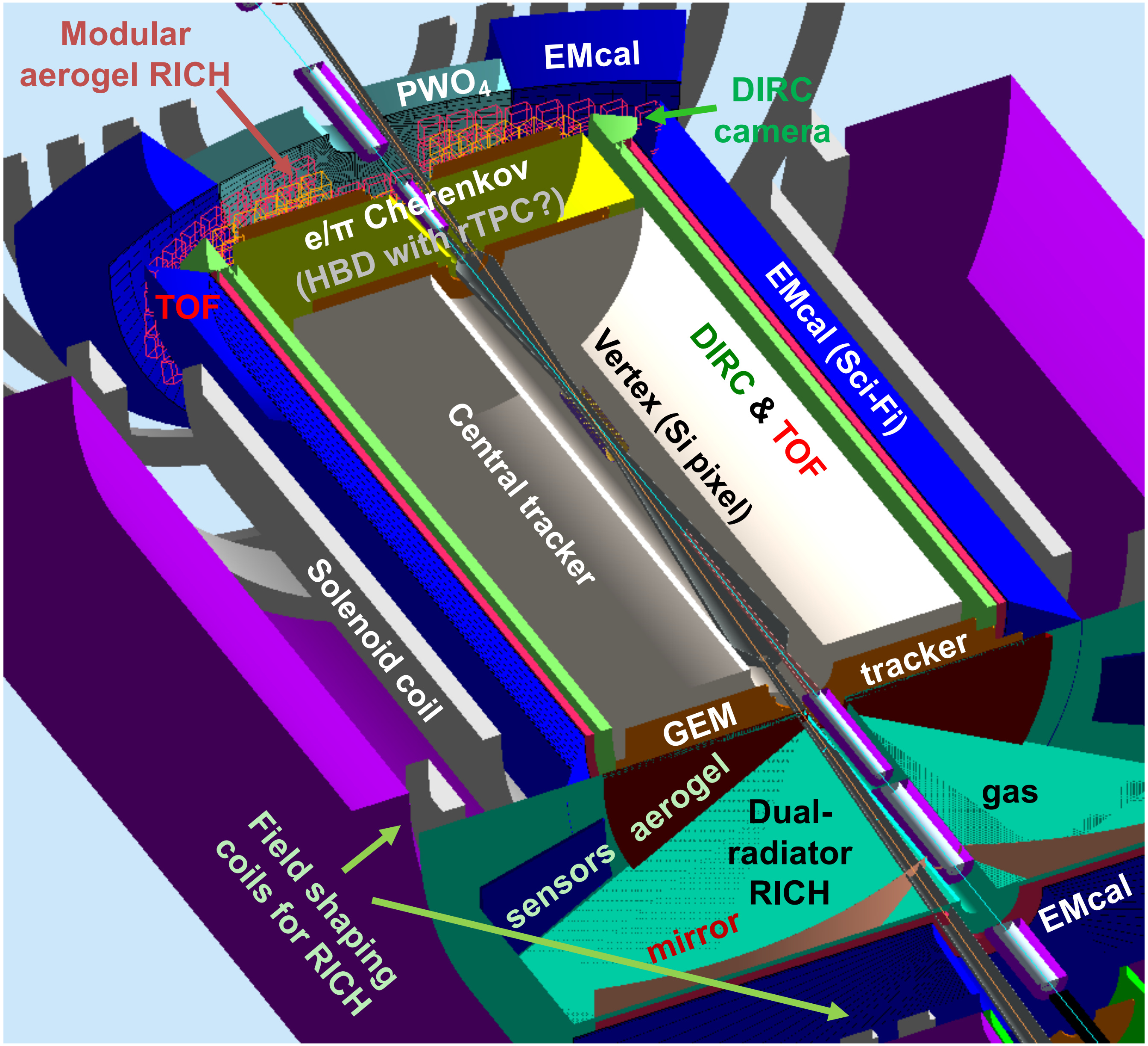
BNL ePHENIX/Celeste EIC central detector



- DIRC, RICH, and TOF systems already considered in current concept.
- Close collaboration with eRD14 expected in preparation of new, updated ePHENIX LOI.

N. Feege, EIC UG meeting, Jan 2016

JLab EIC central detector showing PID integration



- All eRD14 systems (DIRC, mRICH, dRICH, and TOF) are part of the baseline JLab detector concept.

Dual-radiator RICH (dRICH)

Goal:

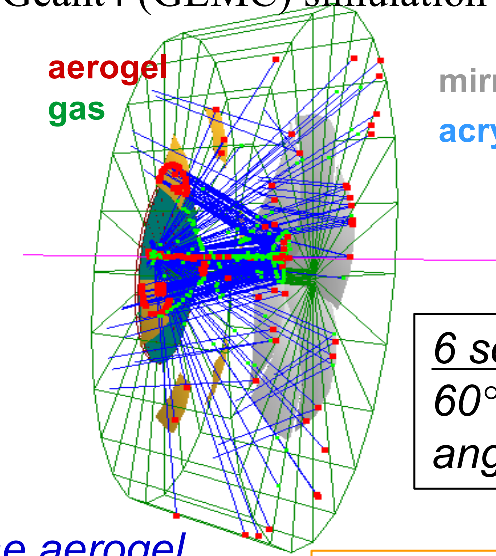
- Continuous coverage for >50 GeV/c for pi/K and >10 GeV for e/pi
- First such device developed for endcap of solenoidal detector

FY 17 progress:

- Integration of aerogel and gas radiators (acryllic shield)
- Improved simulation (Rayleigh scattering, realistic aerogel, etc)

Dual-radiator RICH (dRICH)

Geant4 (GEMC) simulation



mirror R = 2.8 m

acrylic filter

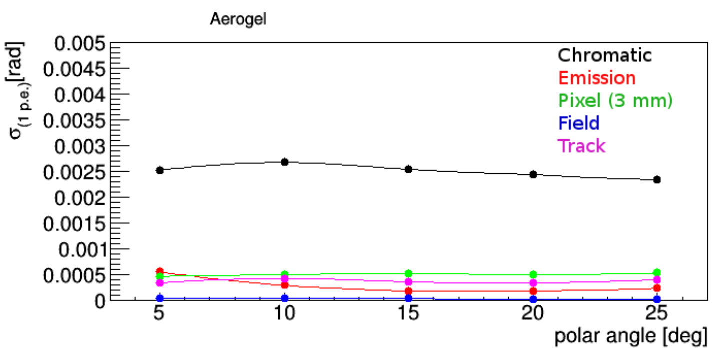
Dual - radiator: aerogel (n=1.02) & C_2F_6 gas

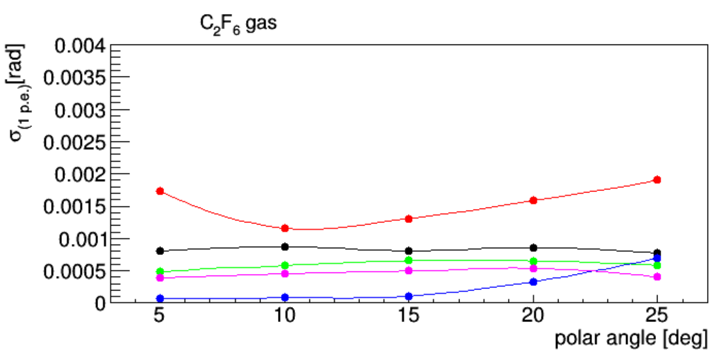
in outward reflecting mirror configuration
(focal plane away from the beam,
reduced area and background)
d*RICH is in magnetic field (3T in the simulation)*

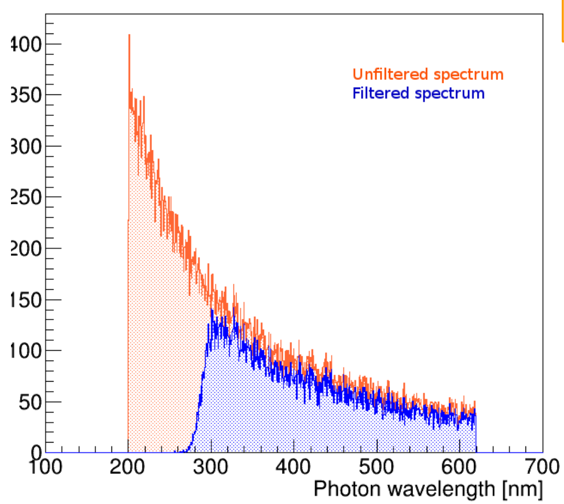
1 p.e. error sources contributions re-evaluated
in a configuration with an acrylic shield in front of the aerogel

6 sectors of 60° in azimuthal angle

Photo-detector:
spherical shape
8500 cm² (per sector)
pixel size 3 mm



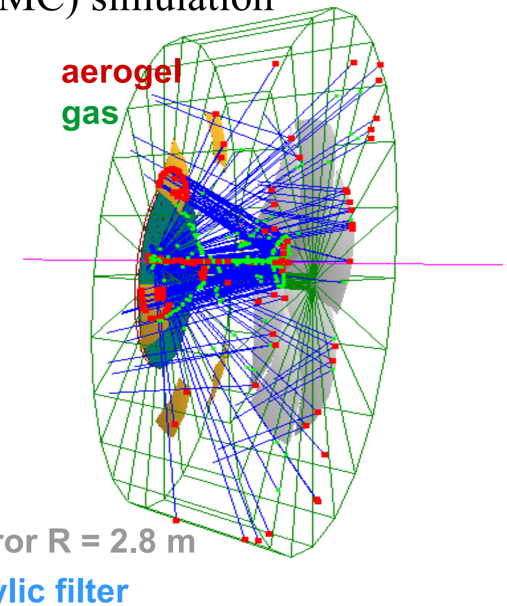




A 3mm thick acrylic filter has been applied, in front of the aerogel, to minimize Rayleigh scattering effects

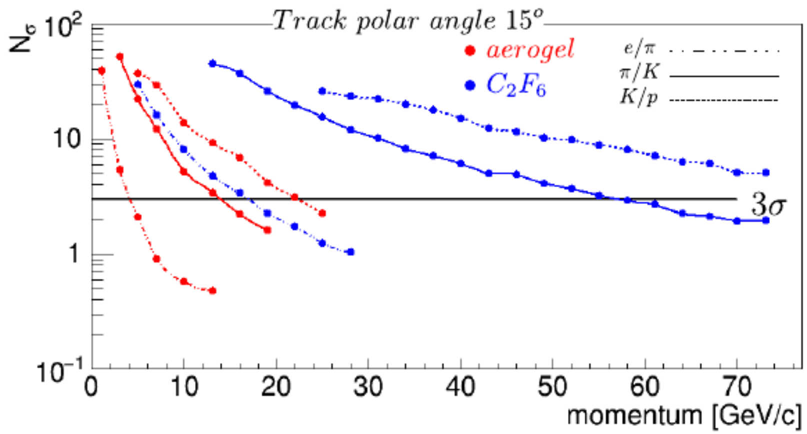
Dual-radiator RICH (dRICH)

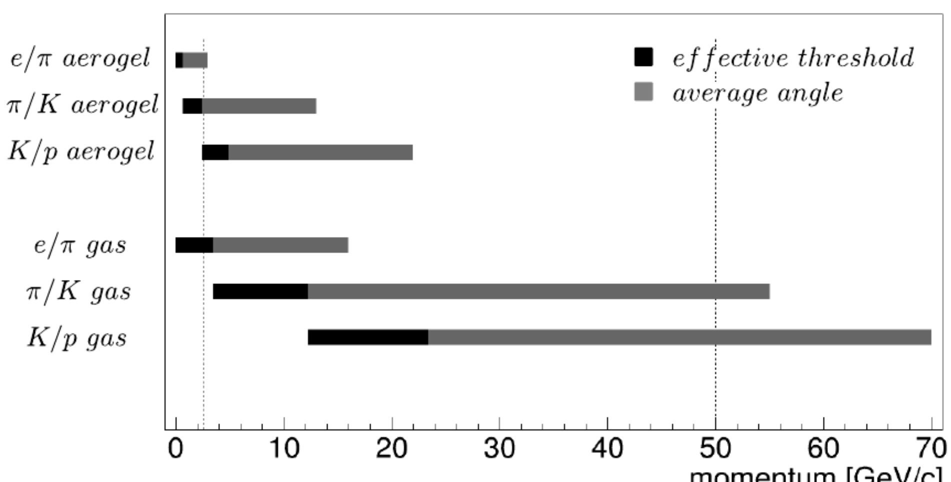
Geant4 (GEMC) simulation



Reconstruction by Inverse Ray Tracing algorithm with a QE curve following that of the Hamamatsu H12700 - 03 multi-anode PMT

Discrimination power for particle species





- Properties of the aerogel used for the simulation inferred from detailed prototyping studies of CLAS12 RICH collaboration
- All the main optical processes (i.e. Rayleigh scattering) are included in the simulation

n=1.02 allow pi/K separation beyond 10 GeV/c at 3 sigma

dRICH – future activities

- Identification of photosensor candidates (SiPM, MCP-PMTs) and implementation in the simulation
- Investigation of how much resolution can me improved by more advanced reconstruction algorithms
- Simulation of a compact version of the dRICH to better fit the EIC detector concepts developed at BNL, and an evaluation of feasibility and performance using the current parameters for the magnetic field (*work has started on an ePHENIX implementation)*
- Formulation of requirements on the EIC detector for optimal RICH performance
- Study and definition of a small-scale prototype for FY18

Modular aerogel RICH (mRICH)

Goal:

- Compact device with coverage up to 10 GeV/c for pi/K
- First aerogel RICH with lens-based focusing (for performance and cost)

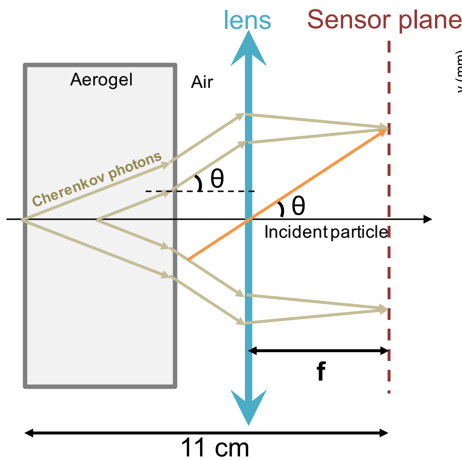
FY 17 progress:

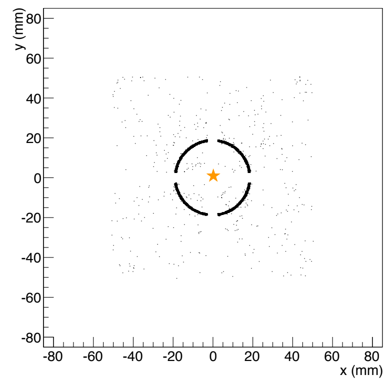
- Completed analysis of first test beam, validating simulation of photon yields
- Paper with test beam results submitted
- Design study for second prototype (to validate PID performance)

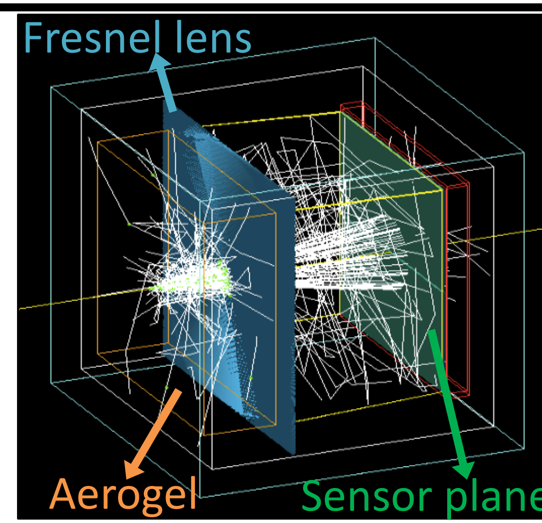
mRICH – lens-based focusing aerogel detector design

Smaller, but thinner ring improves PID performance and reduces length

Lens-Based mRICH Design

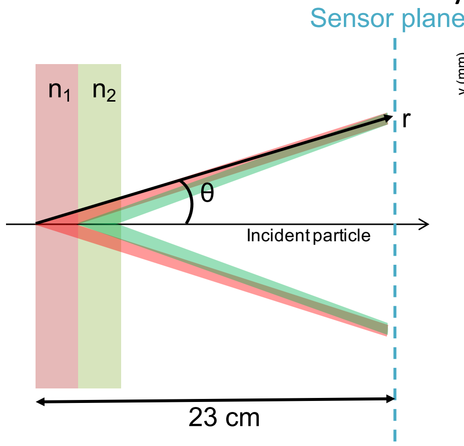


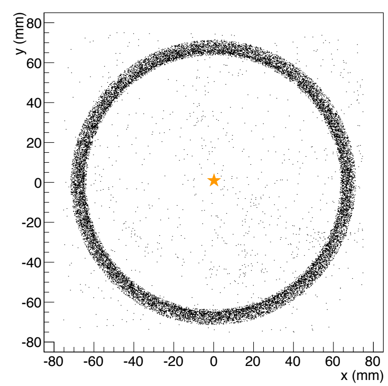




9 GeV/c pion beam launched at the center of xy plane in simulation

Two-Layer Proximity Focusing Design (BELLE-2 ARICH)



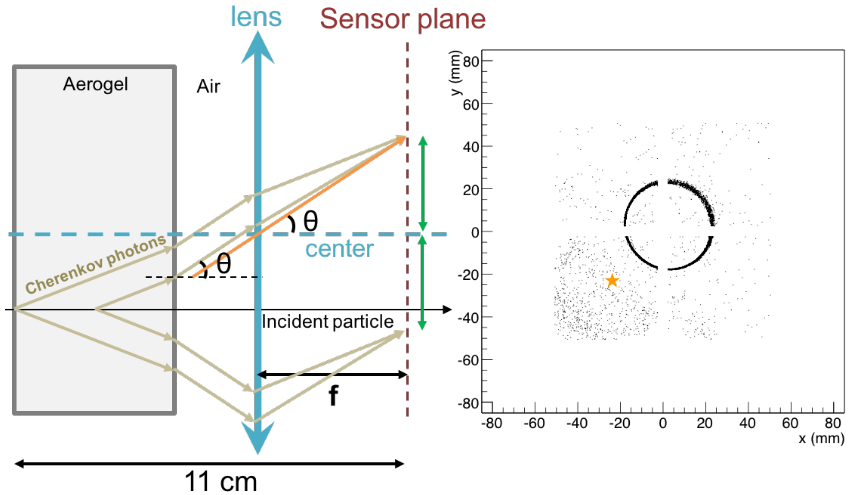


- EIC mRICH designed for K/pi ID up to 10 GeV/c
- BELLE-2 ARICH design aims to separate pion and kaon up to 4 GeV/c

mRICH – lens-based focusing shifts image to center

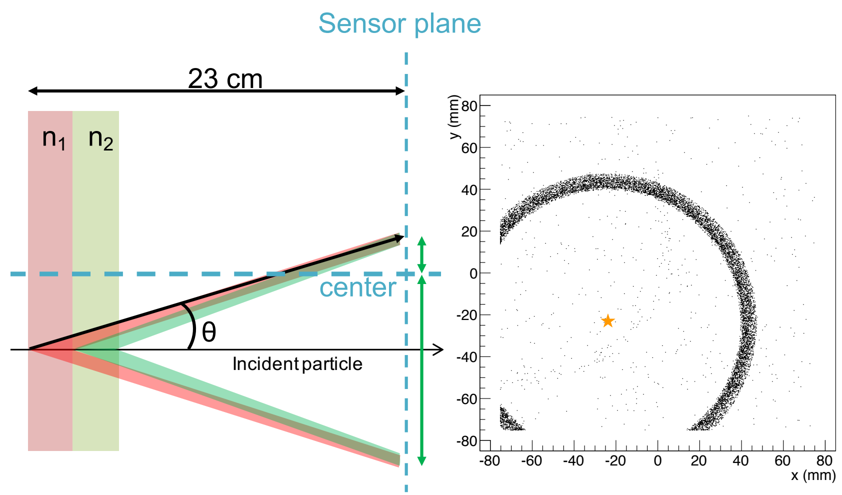
Ring centering of lens-based optics reduces sensor area (main cost driver)

Lens-Based mRICH Design



- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring image is **center** on the middle of the sensor plane

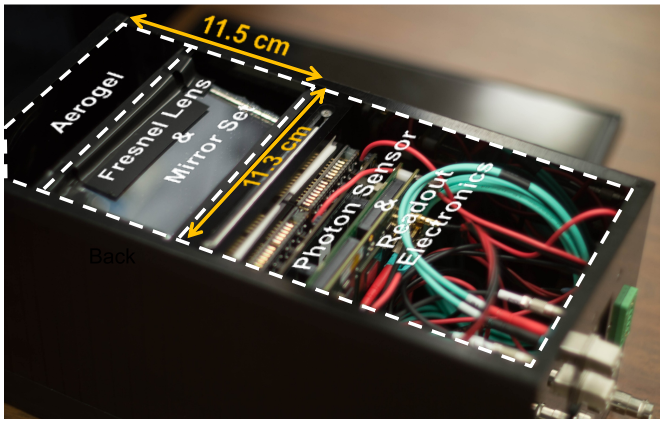
Two-Layer Proximity Focusing Design (BELLE-2 ARICH)



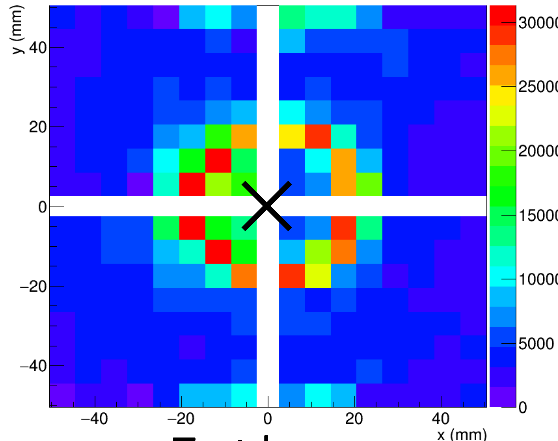
- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring is centered at point of incidence

mRICH – 1st test beam results

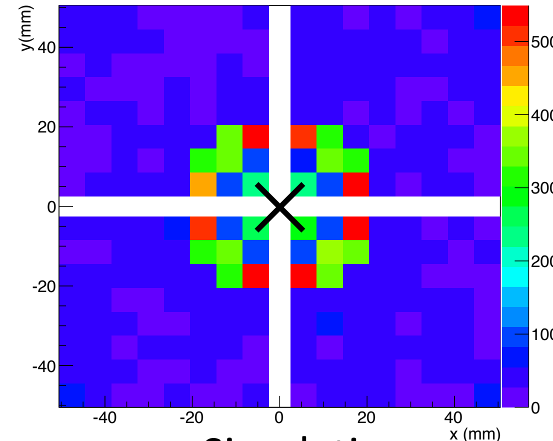
The 1st test beam result verified mRICH working principle and validated simulation



1st mRICH prototype was tested at Fermilab Test Beam Facility in April 2016



Test beam



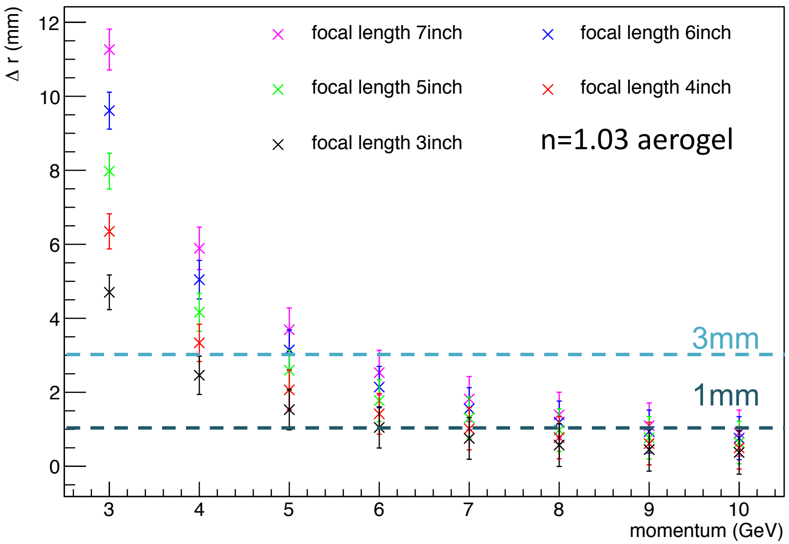
Simulation

	Analytical Calculation	Test Beam Data	Simulation
Radius (mm)	19.4	19.0 ± 1.3	18.9 ± 1.0
Number of detected photons per event	10.4	11.0 ± 2.9	11.1 ± 2.9

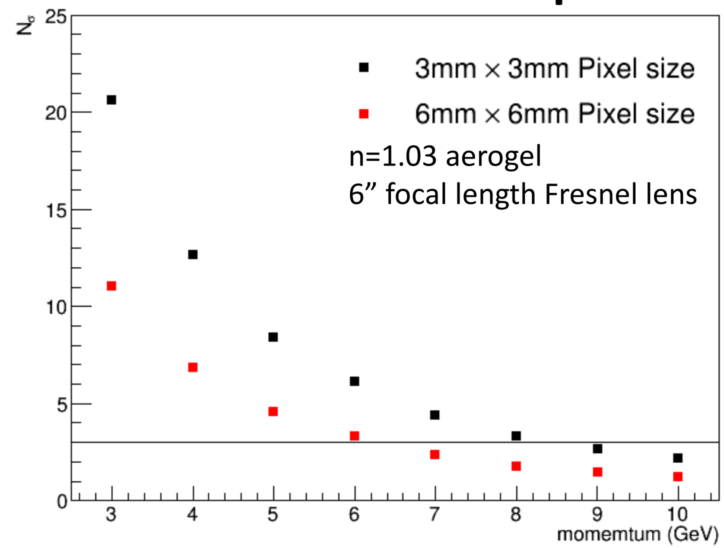
Simulation provides an accurate description of measured photon yield

mRICH – optimization of PID performance

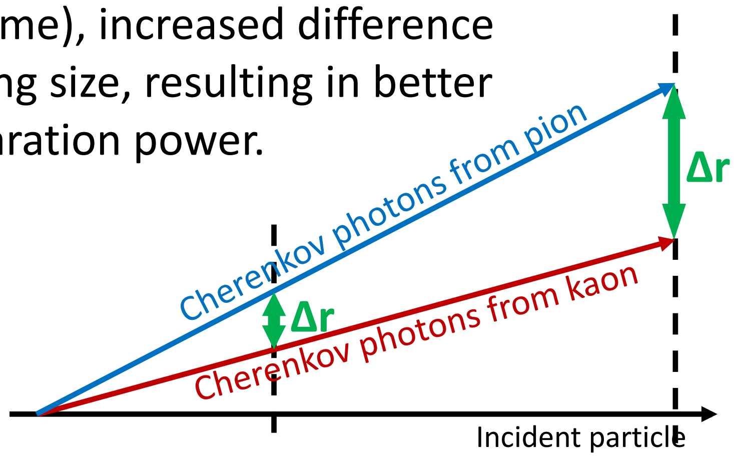
1. Fresnel lens with longer focal length



2. Sensors with maller pixel size



Longer focal length (expansion volume), increased difference in ring size, resulting in better separation power.

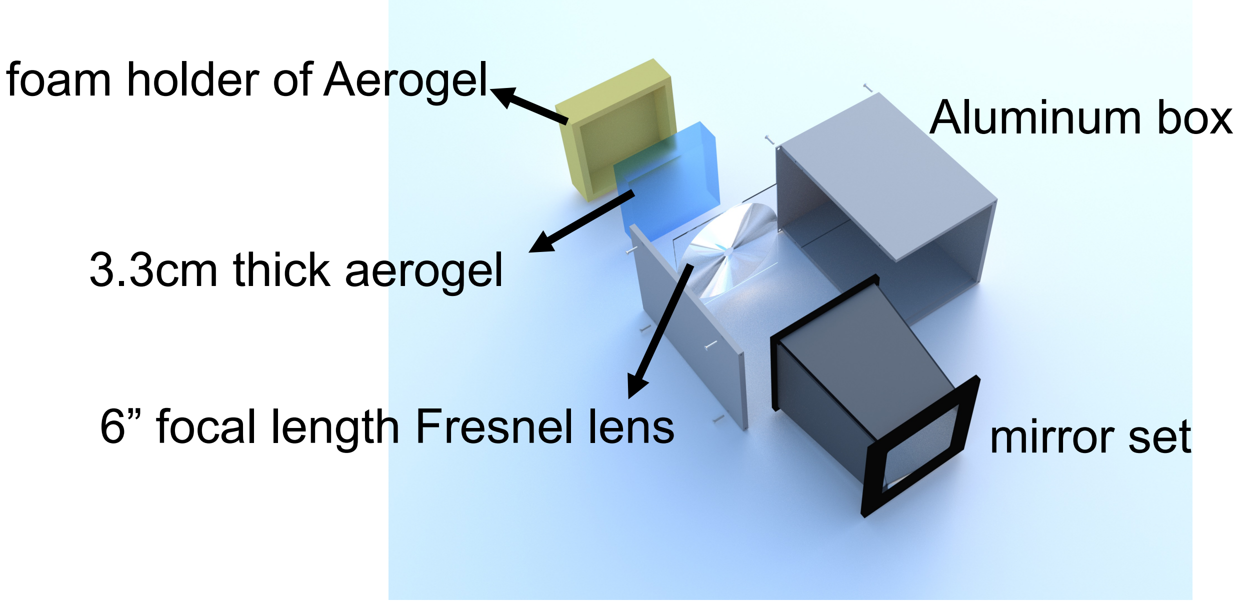


To test the PID performance, the 2nd prototype will use

- A 6" focal length Fresnel lens (r≈38mm at 10 GeV/c)
- 3×3mm^2 pixel size sensors

mRICH – FY17 goals

1. Publication in NIM A, arXiv
2. Implementation of the mRICH in a full EIC detector simulation (fsPHENIX and ePHENIX at BNL)
3. Preparation of a second prototype for tests in FY18



High-performance DIRC

Goal:

- Very compact device with coverage up to 10 GeV/c for p/K, 6 GeV/c for π/K, and 1.8 GeV/c for e/π, pushing performance well beyond state-of-the-art
- First DIRC aiming to utilize high-resolution 3D (x,y,t) reconstruction (performance and cost)

FY 17 progress:

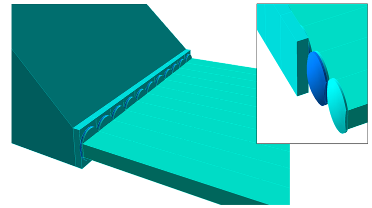
- Completed analysis 2015 CERN test beam data, validating lens simulation used for establishing EIC DIRC performance
- Focal plane of lens prototype mapped on optical bench
- Progress on analysis of 2016 CERN data, aimed at refining time-based reconstruction for both regular and wide radiator bars (plates)
- Initial studies of advanced cylindrical lens for wide radiator bar geometry

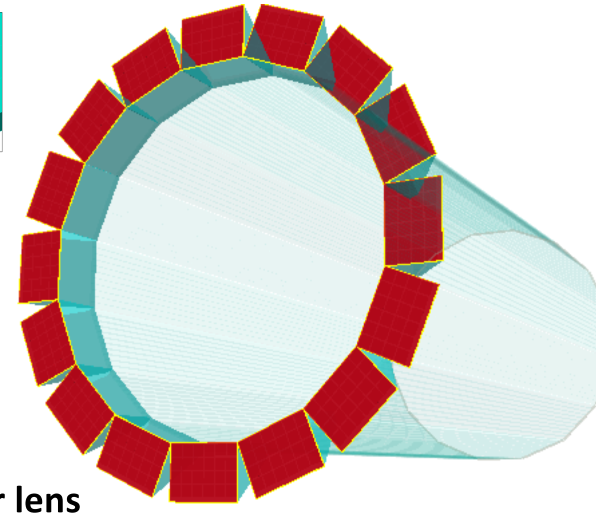
DIRC – overview

High-Performance DIRC simulations

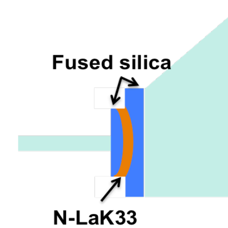
- The EIC DIRC with 3-layer lens will push performance beyond state-of-the-art to achieve 1 mrad Cherenkov angular resolution per track
- Time-based reconstruction has potential to significantly improve momentum coverage
- Paper on high-resolution DIRC published in JINST

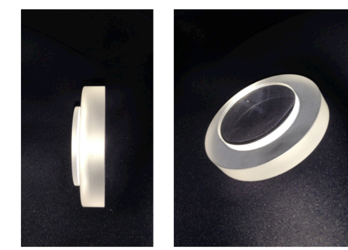
High-performance DIRC in Geant4





3-layer lens

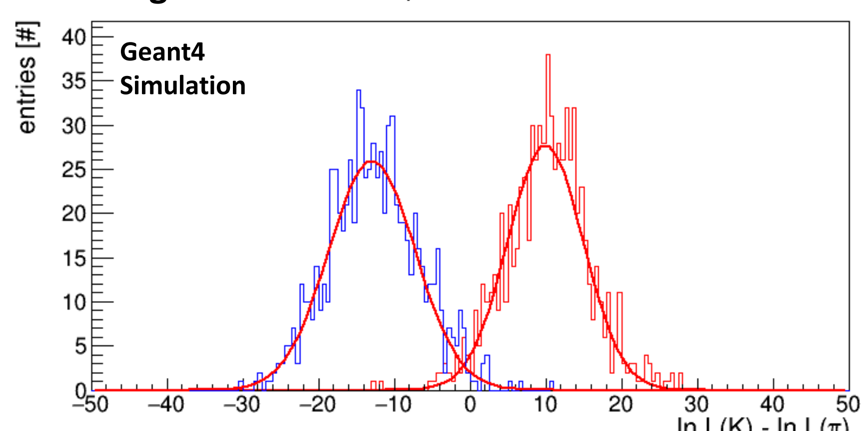




Experimental tests of 3-layer lens

- Mapping focal plane
- Radiation hardness test
- Performance in prototype placed in particle beam (synergy with PANDA Barrel DIRC group)

Simulated 4.3σ π/K separation at 6 GeV/c using time-based reconstruction in narrow bars



Wide bar (plate) radiator geometry

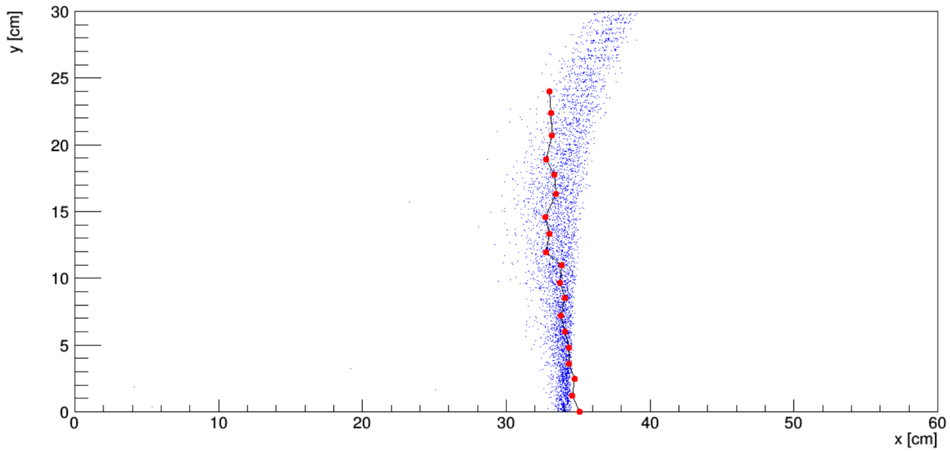
- Development of alternative time-based reconstruction method
- Possibility of reducing cost without compromising performance

3-layer lens – focal plane

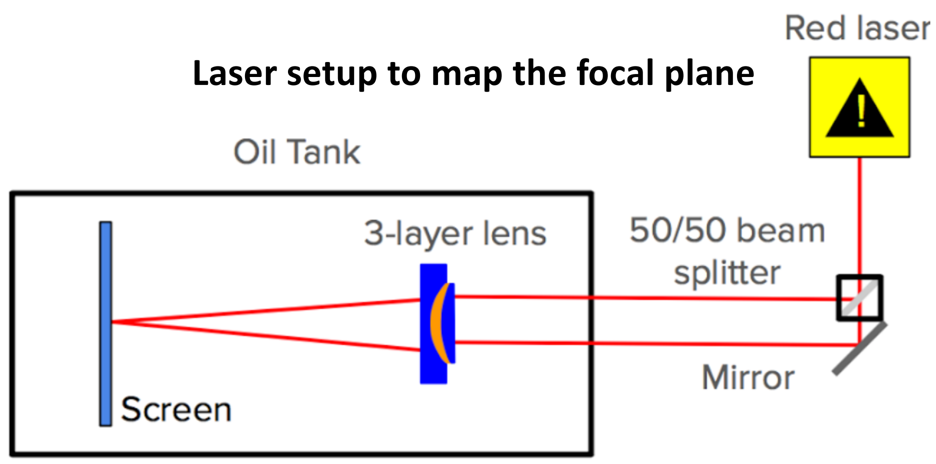
Mapping focal plane of 3-layer lens:

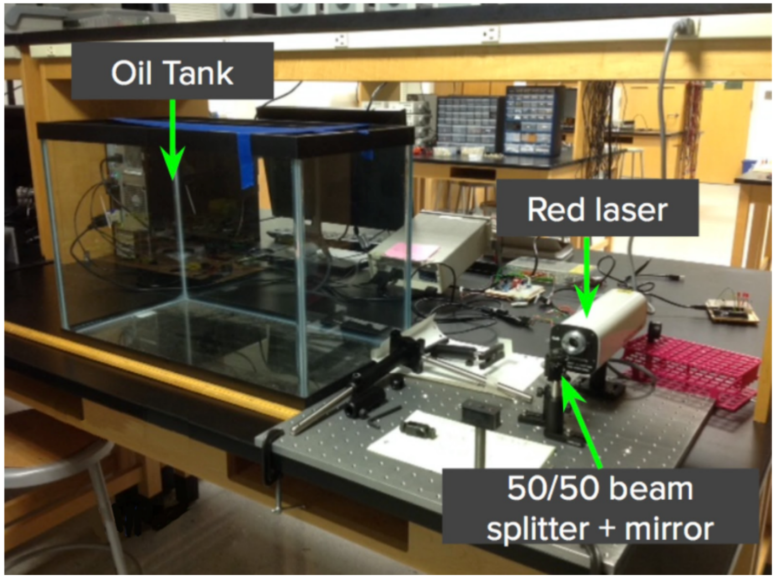
- Lens holder designed to rotate in two planes
- First results of measurements confirm desired flat focal plane
- Analysis of data for 3D mapping of the focal plane in progress

Measured and simulated focal plane of the spherical 3-layer lens



Laser setup to map the focal plane



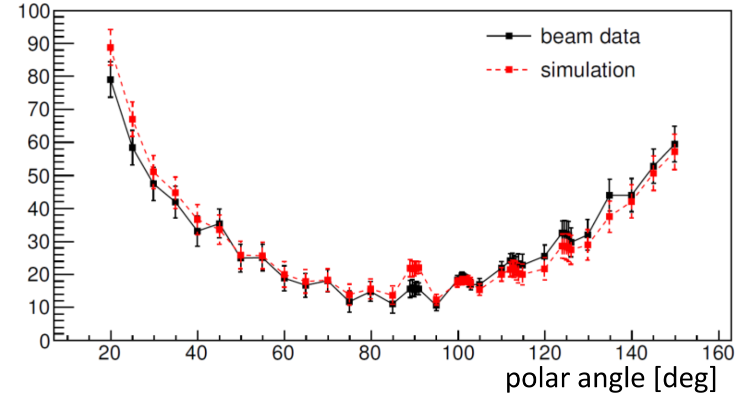


3-layer lens – beam tests

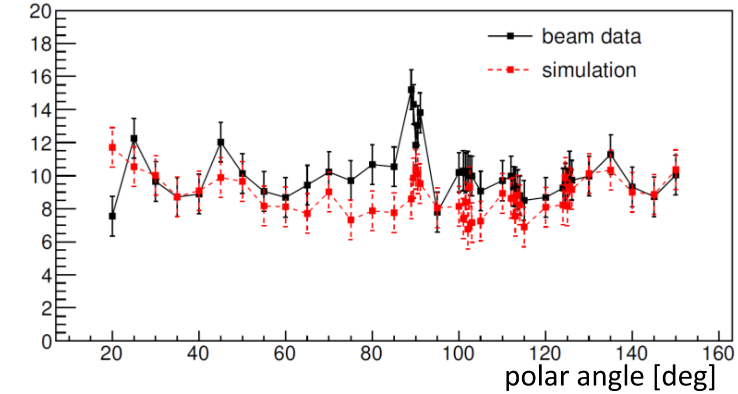
The performance of the spherical 3-layer lens has been validated using the PANDA Barrel DIRC prototype at CERN PS

- Larger sensor pixels, slower electronics than EIC DIRC: → prototype goal: 3σ π/K separation @ 3.5GeV/c
- Optics similar to EIC DIRC design: narrow bar, fused silica prism, 3-layer spherical lens.
- Measured photon yield, Cherenkov angle resolution per photon (SPR), and per particle ($\Delta\theta_c$), and π/K separation power – all in good agreement with simulation (which is also used to predict the performance of the EIC DIRC)
- CERN2015 data analysis finalized.
- Geant4 simulations validated with test beam data.
- Prototype achieved 3.6σ π/K separation @ 3.5GeV/c, exceeding the PANDA PID performance goal.

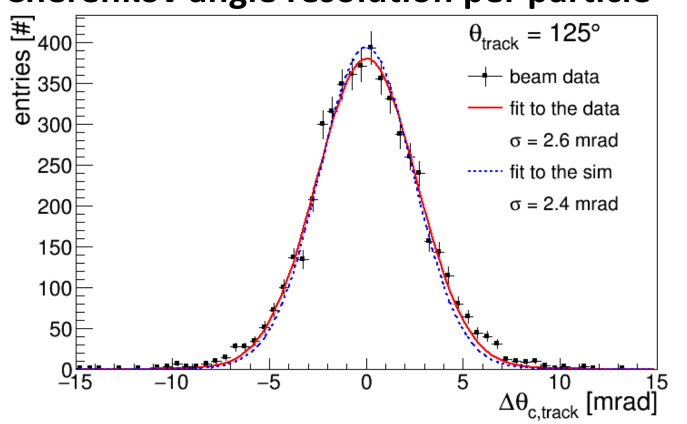
Photon yield



Cherenkov angle resolution per photon



Cherenkov angle resolution per particle

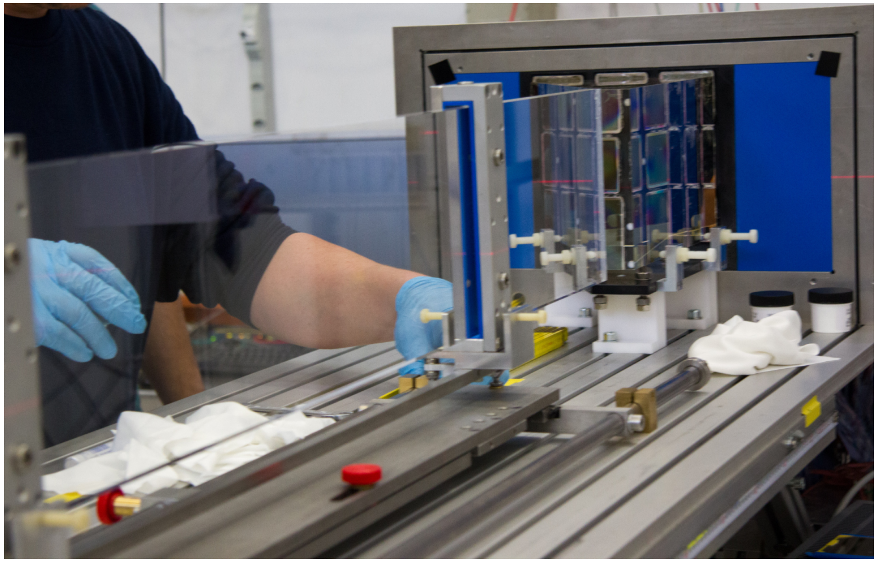


Wide bar (plate) geometry

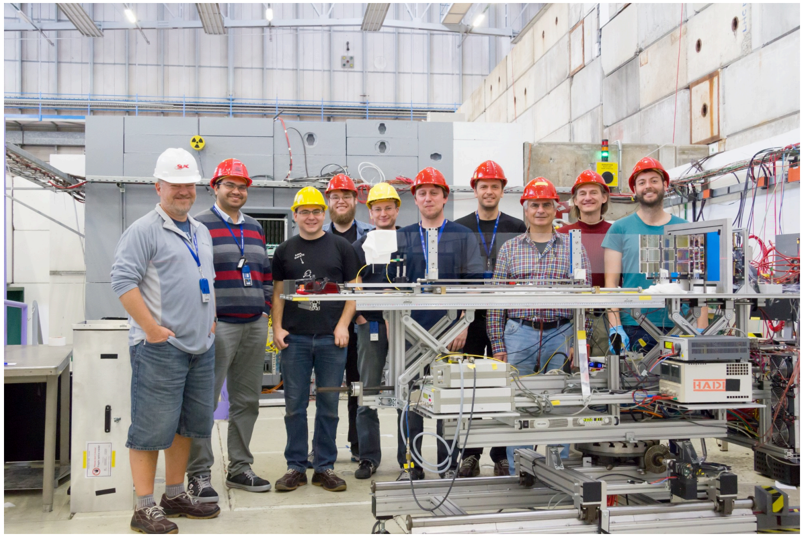
DIRC performance with wide plate as radiator was tested during the 2016 test beam at CERN

- CERN2016 data analysis in progress

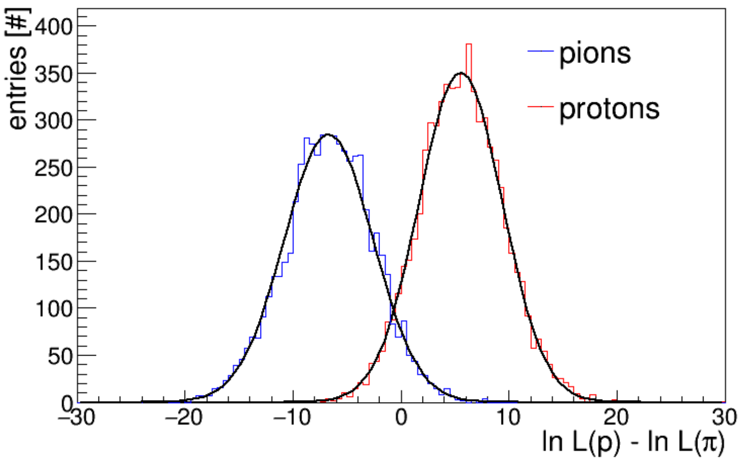
Wide plate coupled to compact prism



PANDA and DIRC@EIC teams at CERN 2016



log-likelihood difference calculated for TOF-tagged proton and pions at 7 GeV/c and 25°



Prelim. result corresponds to
3.1σ π/K separation @ 3.5GeV/c

High-resolution TOF (not funded in FY17)

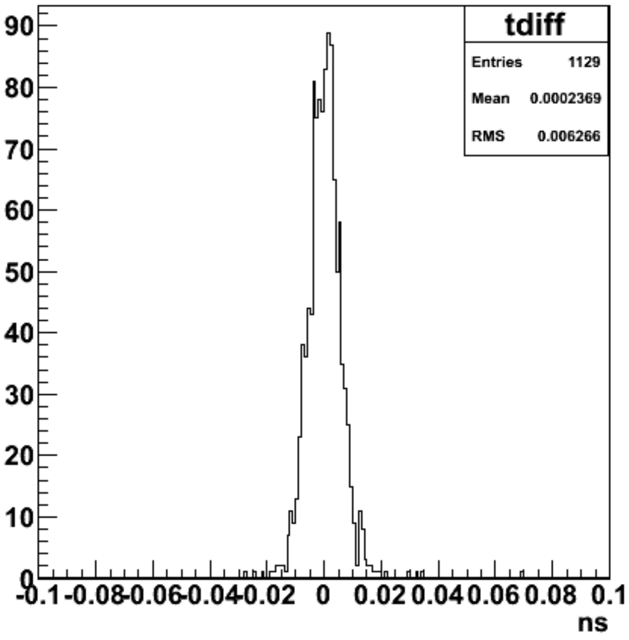
Goal:

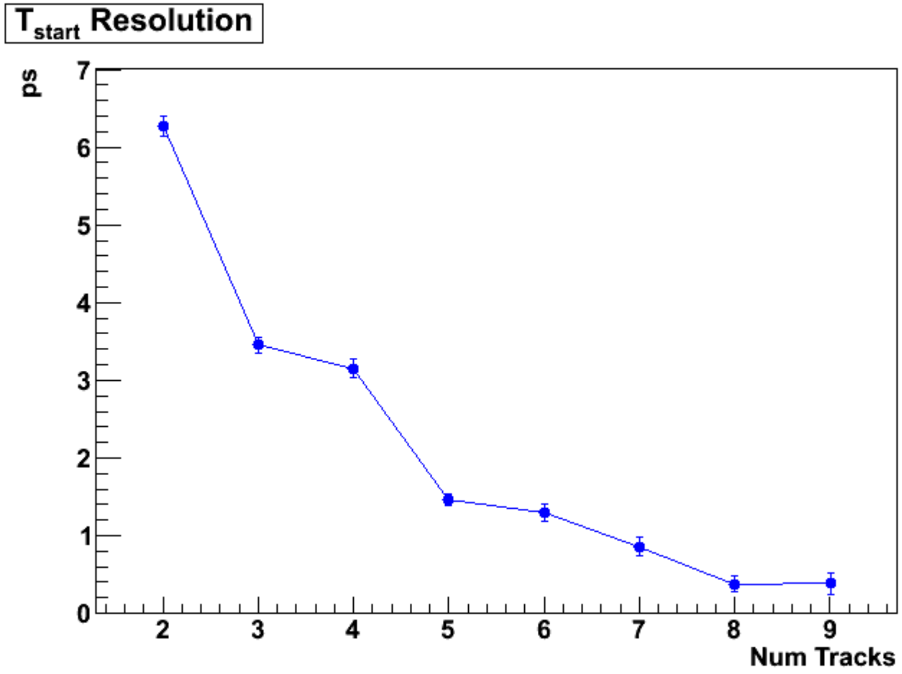
- Explore possibility of achieving very high timing resolution (10 ps)

FY 17 progress:

- Study for obtaining reliable T0 in preparation of future proposal
- Continued work on simulation and testing with external funding

psTOF – self-determined start time study

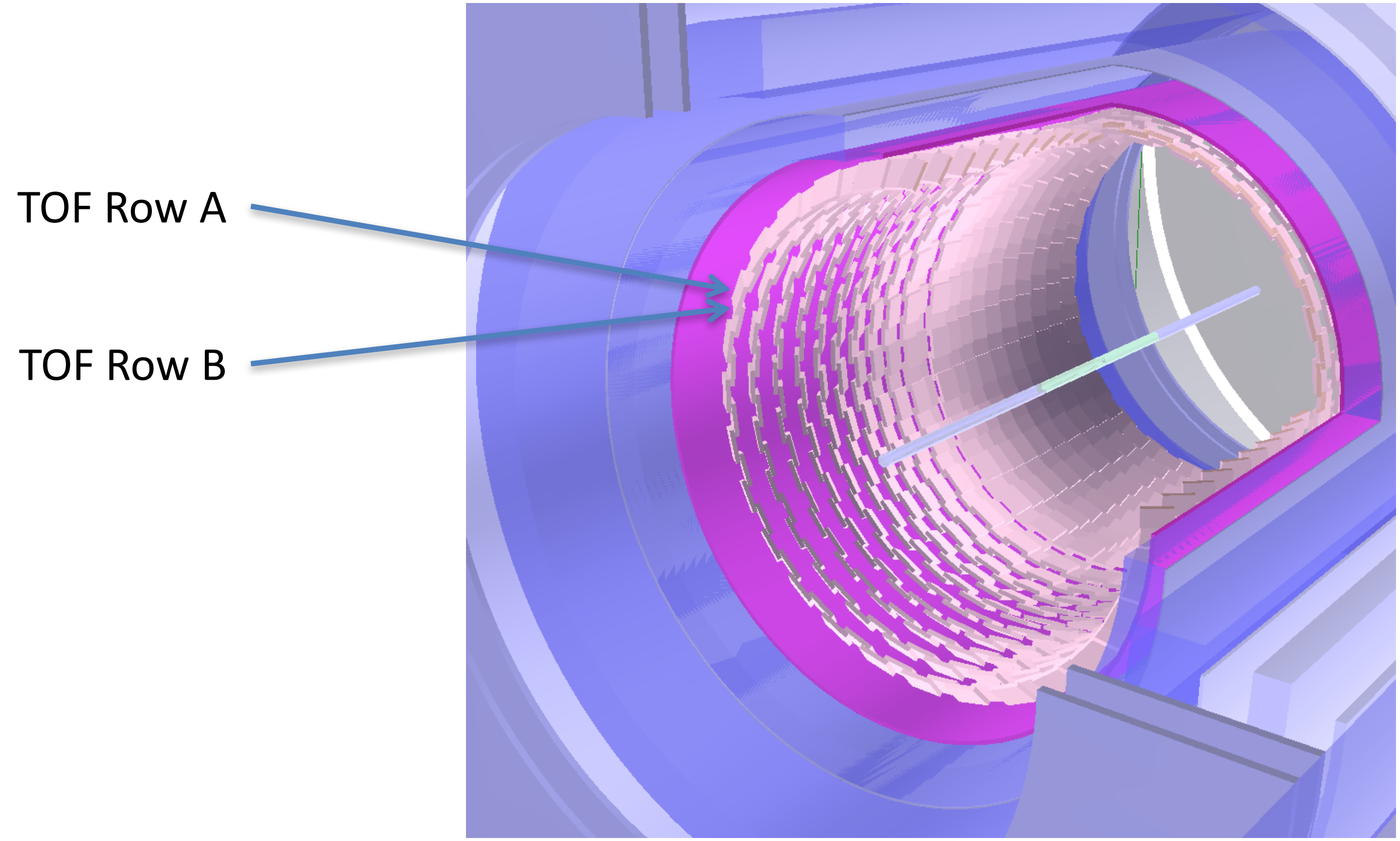




- In e+p collisions, most common TOF question is the lack of a start-time t_0
  - Can be simply solved with 4π TOF, but one can also use a self-determined t_0

- Simple study using particles generated from e+p collisions in PYTHIA6 accepted in barrel (|η|<1.1) shows that a start time can be obtained from fit to several tracks
  - Assuming dt = 10 ps, dp/p = 2%, and dL = 1mm

psTOF – future activities



- Started full GEANT simulation in example detector (sPHENIX)
  - Important to explore dependence on realistic detector effects, albedo, etc.
- Discussions underway with LBNL and consortium of Chinese Univ's to fund mRPC R&D and DRS4-based digitizer board
- SULI student at BNL for next 4 months to continue testing mRPC prototypes with alternative materials, followed by summer students from ACU and Howard
- UV sensitive ANL MCP-PMT to be studied over next 6 months

Photosensors and Electronics

Goals:

- To evaluate current PMTs for EIC-PID detector application and to develop alternative cost-efficient photosensors (LAPPDs).
- To identify and implement viable and cost-efficient solution for readout electronics for PID detector prototypes.

FY 17 progress:

- Gain evaluation of commercially available multi-anode MCP PMTs in magnetic field up to 5 T.
- LAPPDs: new design of HV divider; manufacturing of 10 individual MCP-PMTs; MCP-PMT evaluations.
- Explore and establish synergies with electronics groups (Hawaii, INFN-Ferrara) to adapt existing electronics solutions for EIC-PID prototypes.

Sensors in High-B Fields

Funded Activities

- Requisition of parts and manufacturing of custom components for sensor measurements, such as custom holders, light box end caps, HV divider, *etc*. Cold-magnet operations.

- MCP-PMT gain measurements up to 5 T.

Progress

- Measurement of gain performance of Hamamatsu multi-anode 10-μm PMT and of Photonis 25-μm PMT as a function of field and orientation.

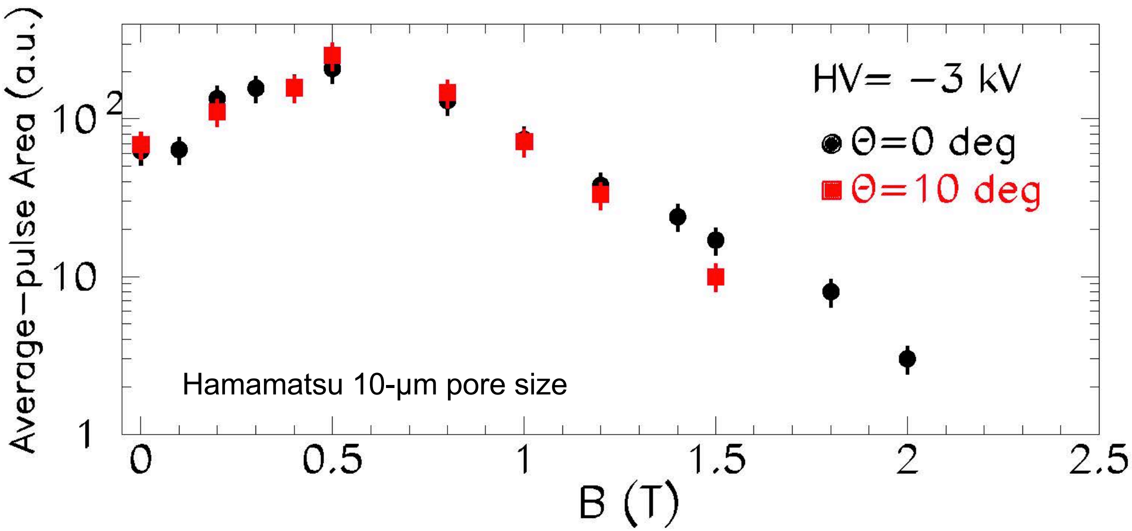
Future

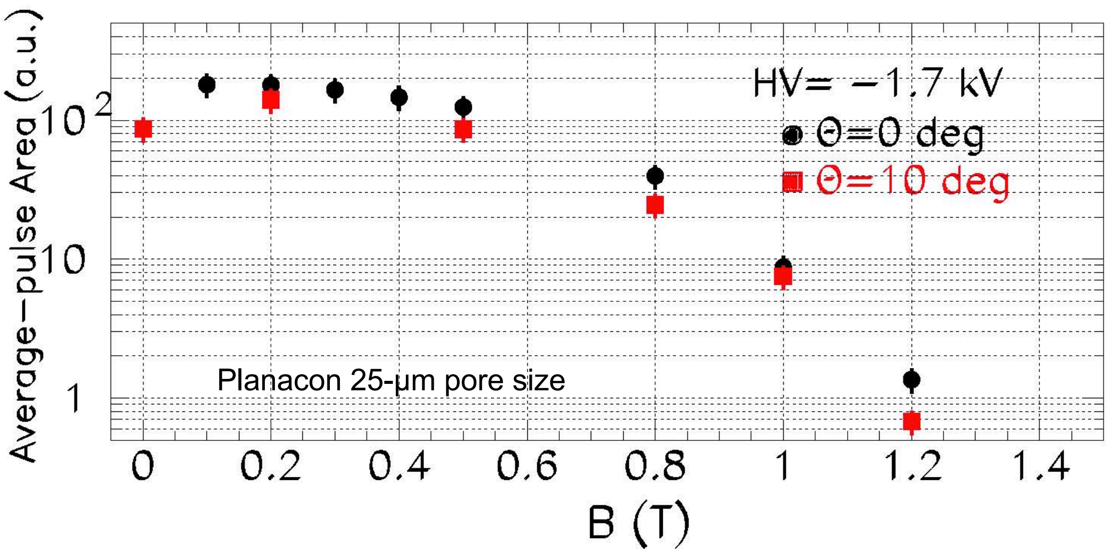
- MCP-PMT gain measurements of multi-anode 10-μm MCP-PMTs from other manufacturers for various operational parameters in B-fields up to 5 T.

- Upgrade of facility with a laser ($20k from ODU/VA) and timing capabilities.

- Development of GEANT simulation of MCP-PMT for studies of MCP-PMT performance in high B-fields for various design parameters.

Sensors in High-B Fields – 2016 Results





- Measurements performed at 96% of maximum allowed high voltage.
- 10-μm sensor
  - Can be operated up to about 2 T at standard orientation.
  - Can be operated up to about 1.5 T at larger angles.
- 25-μm sensor
  - At both orientations sensor can be operated up to about 1.2 T
  - Main objective of measurements is to negotiate 10-μm sensor on loan from Photonis.

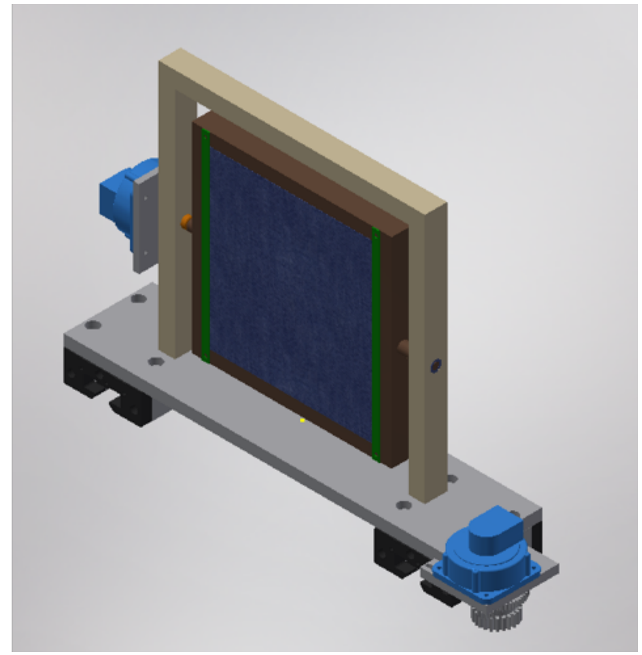
Sensors in High-B Fields – outlook

Future Work funded through EIC R&D

- **Main Goal**: to identify the limitations of current MCP–PMT design and operational parameters for High-B operations; to achieve optimization of these for successful application in DIRC in the high magnetic field of the central detector at EIC.

- **Effort:**
    - Continuation of our close collaborations with all main photosensor suppliers.
    - Commissioning of a universal HV divider that will allow to study gain recovery for **different** photosensors.
    - Further MCP–PMT gain measurements of 10-μm multi-anode MCP-PMTs as a function of various operational parameters.
    - Development and implementation of a GEANT4 simulation of an MCP–PMT for optimization of design parameters.
    - Upgrade of JLab facility for timing studies in high magnetic fields of various commercially available single- and multi-anode MCP-PMTs.
    - Explore synergies with ANL high-B facility.

Sensors in High-B Fields – new facility at ANL

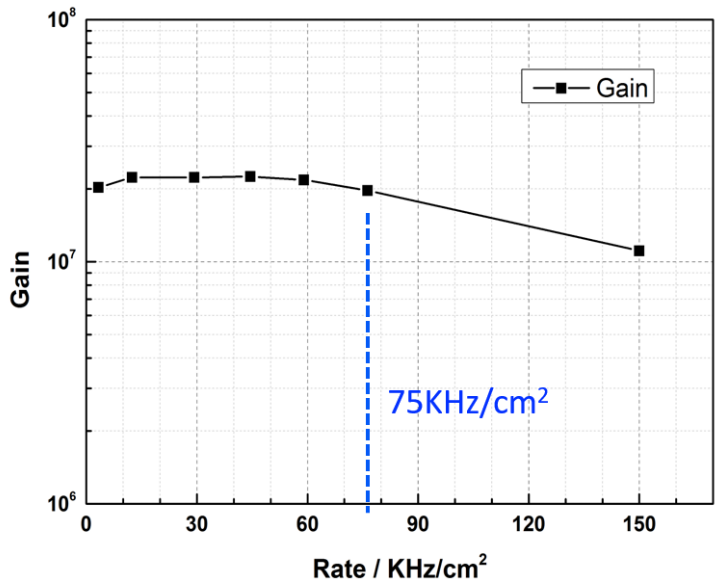


(left) View of the test solenoid facility in the high-bay area at Argonne Bldg. 366.
(right) Test stand for 20 cm x 20 cm MCP magnetic field performance testing.

- A transporter with the capability of testing MCP-PMTs up to 20 cm x 20 cm
- All components are made of non-magnetic materials
- Electrically controlled router
- MCP-PMT center is aligned with the center of the magnetic facility

LAPPDs – results from Fermilab test beam

- In summer 2016, rate capability test experiment data from the FTBF beamline experiment on MCP-PMTs was further analyzed in details.
- The study was done using the 120 GeV proton beam, the beam spot size is about 8 mm^2, and the intensity was varied to achieve fluxes from 3.3-150 KHz/cm^2.



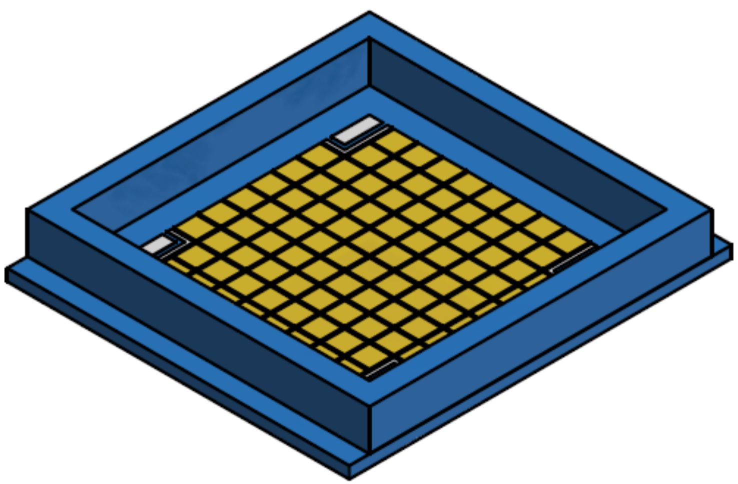
- Did not observe obvious decrease of MCP-PMT gain below 75 KHz/cm^2, indicating good rate capability tolerance, fulfilling EIC requirements.

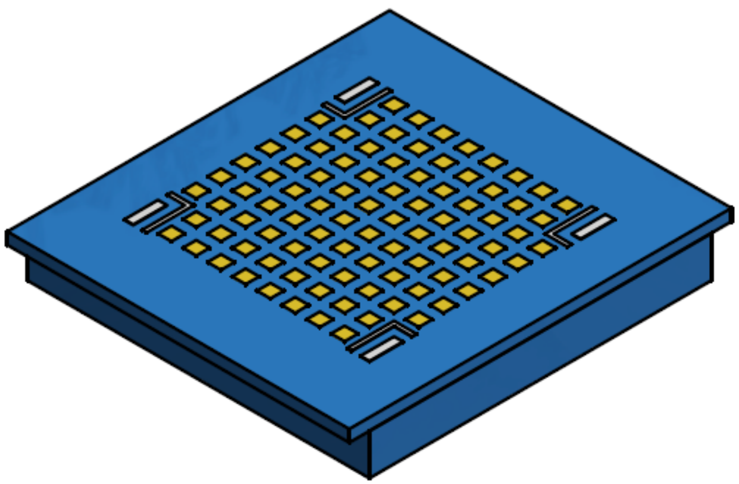
LAPPDs – pixelized (PAD) readout

Current readout design is based on strip line readout
Various applications require pad readout

A new pad readout is designed and currently under fabrication
- Inside and outside pads are made of copper and connected through a VIA
- Base and side walls are made of ceramic
- Version 1: 5 mm x 5 mm pad size and 0.5 mm spacing
- Version 2: 2.25 mm x 2.25 mm pad size and 0.5 mm spacing

Expect to get version 1 pad base soon, and complete the detector in Feb.
get version 2 pad base on Apr, and complete the detector in May.





eRD14 FY17 budget by topic (including overhead)

	requested	awarded	allocated
dRICH	$55k	$27.5k	$47k
mRICH	$85k	$21.25k	$49.75k
DIRC	$98k	$50k	$50k
TOF	$40k	$0	$0
High-B	$55k	$55k	$17k*
LAPPDs	$90k	$90k	$80k
Electronics	$21k	$0	$0
Total	$443k	$243.75k	$243.75k

*) High-B also had an additional ~$29k no-cost extension of FY16 funds, which were saved at JLab towards the end of FY16.

- The 6-month dRICH funding was based on a misunderstanding of the postdoc start date.
- Labor was removed from the mRICH budget, which instead was paid for by GSU. The mRICH hardware funding was adjusted to a minimum required to demonstrate the superior PID performance of the lens-based concept (as requested by the committee).
- One high-B test was postponed to investigate possible synergies with new ANL facility

Recent publications

C.P. Wong *et al*., Modular Focusing Ring-Imaging Cherenkov Detector for Electron-Ion Collider Experiments, submitted to Nucl. Instrum. Meth. A.

A. Deldotto et al.: Design and R&D of RICH detectors for EIC experiments, poster at RICH2016 (9th International Workshop on Ring Imaging Cherenkov Detectors), September 5-9, 2016, Bled, Slovenia, submitted to Nucl. Instrum. Meth. A.

L. Allison: High-performance DIRC detector for use in an Electron-Ion Collider, Proceedings for ICHEP2016 (38th International Conference on High Energy Physics), August 3-10, 2016, Chicago, IL, submitted to Proceedings of Science.

G. Kalicy: PID systems for the JLab EIC full-acceptance detector, Proceedings for ICHEP2016 (38th International Conference on High Energy Physics), August 3-10, 2016, Chicago, IL, submitted to Proceedings of Science.

G. Kalicy et al.: DIRC detector for the future Electron Ion Collider experiment; Proceedings of the DIRC2015 Workshop, 11-13 November, Giessen, Germany, Journal of Instrumentation, 11, C02019 (2016).

Y. Ilieva et al.: MCP-PMT studies at the High-B test facility at Jefferson Lab; Proceedings of the DIRC2015 Workshop, 11-13 November, Giessen, Germany; Journal of Instrumentation, 11, C02019 (2016).

R. Dharmapalan et al: MCP-based photodetectors for cryogenic applications, Journal of Instrumentation, 11, C02019 (2016).

J. Xie et al.: Development of a low-cost fast-timing microchannel plate photodetector; Nucl. Instrum. Meth. A 824 (2016) 159-161.

J. Wang et al.: Development and testing of cost effective, 6cm×6cm MCP-based Photodetectors for fast timing applications; Nucl. Instrum. Meth. A 804 (2015) 84.

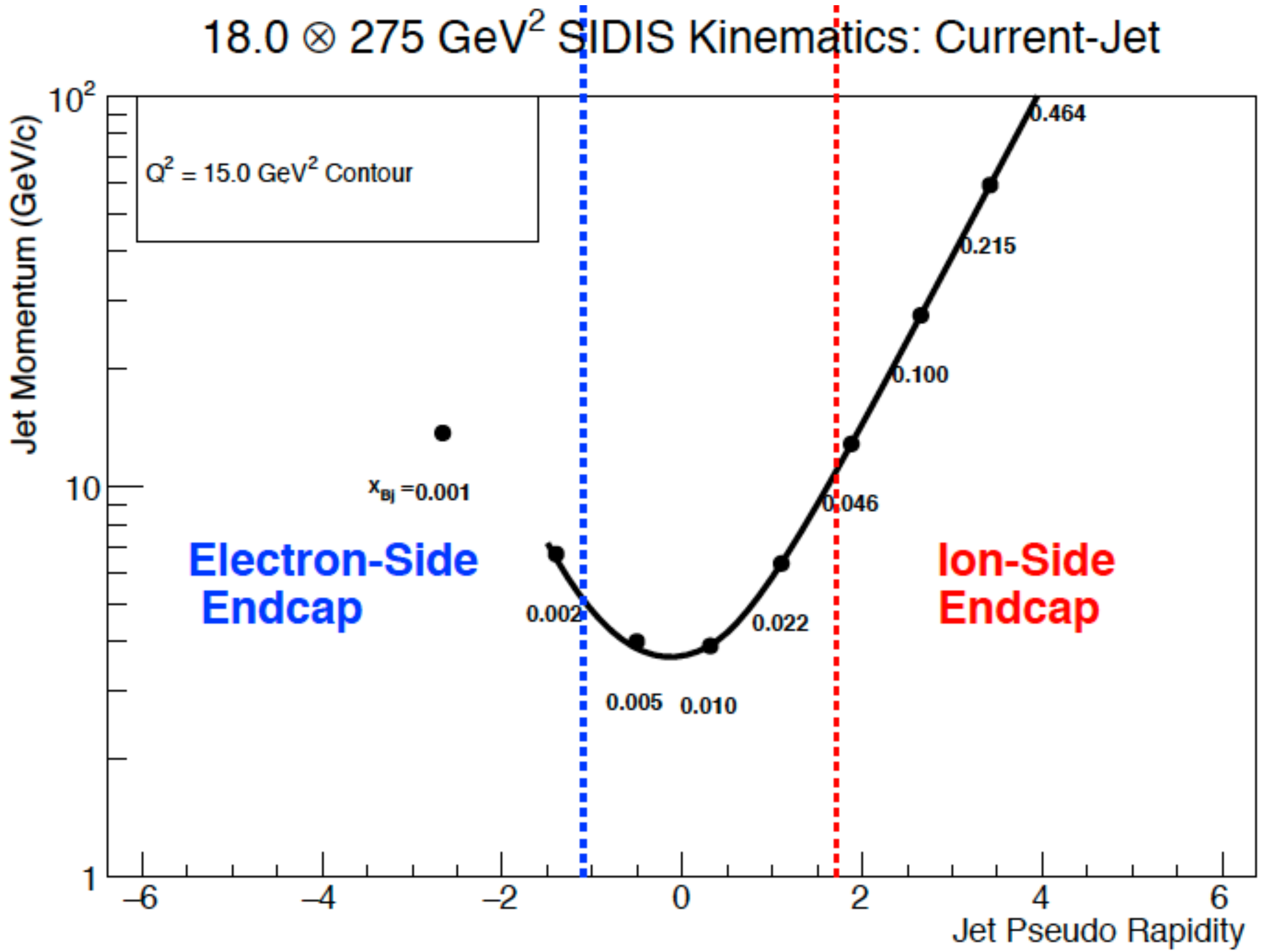
J. Xie et al. (LAPPD collaboration): Design and fabrication of prototype 6×6 cm2 microchannel plate photodetector with bialkali photocathode for fast timing applications, Nucl. Instrum. Meth. A 784 (2015) 242.

Thank you!

Also, please visit the eRD14 wiki

http://phynp6.phy-astr.gsu.edu/eRD14/index.php/Main_Page

Backup



18.0 ⊗ 275 GeV^2 SIDIS Kinematics: Current-Jet
Q^2 = 15.0 GeV^2 Contour
Jet Momentum (GeV/c)
Jet Pseudo Rapidity
Electron-Side Endcap
Ion-Side Endcap
x_{Bj} =0.001
0.002
0.005
0.010
0.022
0.046
0.100
0.215
0.464

Particle distributions